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The Impact of Radio Frequency Interference (RFI) on VLBI2010

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Abstract

A significant motivation for the development of a next generation system for geodetic VLBI was to address growing problems related to RFI. In this regard, the broadband 2-14 GHz frequency range proposed for VLBI2010 has advantages and disadvantages. It has the advantage of flexible allocation of band frequencies and hence the ability to avoid areas of the spectrum where RFI is worst. However, the receiver is at the same time vulnerable to saturation from RFI anywhere in the full 2-14 GHz range. The impacts of RFI on the VLBI2010 analog signal path, the sampler, and the digital signal processing are discussed. In addition, a number of specific RFI examples in the 2-14 GHz range are presented.

1. Introduction

RFI is any man-made radio transmission inadvertently added to a signal of interest. It can originate from land, marine, aeronautical, or space-based transmitters and for purposes ranging from commercial broadcast to scientific and amateur. The entire VLBI2010 spectrum from 2-14 GHz is allocated to a myriad of applications through international, national, and regional agreements with only a tiny portion set aside for radio astronomy. Fortunately, interferometric techniques are comparatively robust against RFI. This is particularly true for VLBI where the antennas are typically so far apart that the sources of RFI at either end of a baseline are different and hence uncorrelated. Even when the RFI is correlated, as happens with geostationary satellites, the RFI output appears at a delay and fringe rate that are almost always significantly different from that of the astronomical signal.

2. The Impact of RFI on the VLBI2010 Analog Signal Path

In an idealized linear analog system, RFI can be analyzed simply as noise added to the astronomical signal. It has essentially the same impact as an increase in the system noise temperature (Tsys). If the RFI is band-limited, as is usually the case, the only region of the spectrum that is degraded is the region where the RFI actually exists. Provided that RFI is not too large, the VLBI2010 analog signal path can be analyzed under the linear assumption.

However, when RFI is larger, the situation is not so simple. The output of real analog devices cannot increase beyond a specific limiting voltage. As the input to the device increases, the output eventually hits this voltage, and it is said that the output is clipped or limited. The process is referred to as saturation. Under operational conditions, this occurs when RFI is much larger than the input astronomical signal. Since the small astronomical signal then rides almost unnoticed on top of the much larger RFI signal, it disappears entirely when the RFI is clipped. This obviously degrades the entire radio astronomical spectrum and not just the region of the spectrum where RFI occurs. To make matters worse, clipping generates harmonics and other intermodulation products of the RFI, which spreads the RFI across the entire spectrum. In this way, even narrow band RFI, if large enough, can destroy an entire input band. This obviously has serious implications for the broadband 2-14 GHz input range of the VLBI2010 system where even a single source of strong RFI anywhere in the spectrum can bring down the entire system.

A proper analysis of saturation potential includes the entire analog signal chain. It is important to optimally adjust the gains of each stage in the chain to maximize the range of linear operation. If suitable devices are available and affordable, the range of operation can be increased by substituting higher dynamic range devices at critical points in the signal path. For VLBI2010, a dynamic range of 30 dB for the full analog signal path is a desirable and realistic target.

If the RFI level after optimal design of the analog signal path is still too large, another solution is to insert a filter to remove the region of the spectrum where the RFI occurs. To be effective, the filter must be inserted prior to the first point where saturation occurs. Under many circumstances this requires that the filter be inserted between the feed and front end Low Noise Amplifier (LNA). If this is the case, the filter must be cryogenically cooled to avoid unacceptable noise performance, and the front end must be mechanically and electrically designed to allow for the insertion of the filter.

Although not immediately obvious, the broadband frequency range of the VLBI2010 system also helps mitigate against saturation. This is particularly true for comparatively narrow band RFI. As an example consider RFI that has a spectral density as high as 70 dB above the noise floor but with a bandwidth of only 1 MHz. Since the 12 GHz LNA bandwidth is a factor of 12,000 greater than that of the LNA, the total RFI power ends up being only about 29 dB above the integrated noise power of the LNA. As a result, this apparently high level of RFI is easily within the dynamic range of a typical VLBI LNA.

Another RFI mitigating factor is the directionality of the parabolic antennas used in VLBI. The RFI power received through antenna sidelobes and backlobes is significantly attenuated relative to that of the astronomical signal of interest which is received along the axis of the antenna.

3. Impact of RFI on the VLBI2010 Sampler

In modern VLBI systems, most back-end receiver functions are now performed digitally. The device that converts the analog input signal into a time-tagged sequence of digital values is the sampler. To ensure adequate fidelity in the digital processing and enough dynamic range to handle RFI, a fairly high resolution 8- to 10-bit sampler is typically used.

In VLBI post-processing, the absolute scale of the input signal is of no consequence. Hence, its digital representation can vary within a settable constant factor. In practice, this variation is accomplished by either attenuating or amplifying the analog signal before it is sampled. The setting of this constant factor is, however, not arbitrary. If the attenuation is too high (resulting in a level that is too small), the signal is then very coarsely sampled. This transforms the smooth analog input into a *squared-up* signal with discrete steps that are large compared to its amplitude. On the other hand, if the input level is too large, the signal can exceed the maximum range of the sampler. This essentially saturates the sampler and clips the output. What is desired is a compromise that minimizes the net degradation.

Fortunately, correlation processing is not very sensitive to these sorts of signal distortions. Take as an example an 8-bit sampler which has a range of roughly ± 128. If the attenuator setting results in an rms digital output anywhere in the surprisingly wide range of 1 to 128, the degradation in correlated signal-to-noise ratio (SNR) is no more than about 10%; if it is set for an output anywhere in the range of 2 to 64, the SNR loss is never more than about 2%; and, if it is set in the output range of 4 to 32, the loss is never more than about 0.5%.

However, the situation becomes somewhat more complicated when RFI is present. The attenuator setting must then be adjusted to simultaneously satisfy restrictions imposed by both the RFI and the system noise. At the upper end, the RFI should never be allowed to saturate the sampler. In practical terms, this means that the rms RFI level should not be allowed to rise above about one quarter of the full range of the sampler. At the lower end, the digital value of the rms system noise should never be allowed to decrease below a value where the correlated SNR loss is more than a few percent. Thus, for an 8-bit sampler, the rms RFI level should be kept below about 32, and the rms system noise should be kept above about 2. This represents a dynamic range of $32/2 = 16$, which is equivalent to a power ratio of 24 dB. For a 9-bit sampler the dynamic range is about 30 dB; and for a 10-bit sampler it is about 36 db.

If the RFI is narrow band, a notch filter in cascade with the sampler antialias filter might be considered an acceptable solution to excise the RFI. However, this is not desirable for the VLBI2010 system where the individual bands are designed to be arbitrarily settable in the full 2.2-14 GHz range. In this case, the notch filter would be appropriate for one frequency setting of the band but not for others.

One simple scenario for setting the pre-sampler attenuator would be to continuously adjust its value to ensure that the rms digital value always stays as near as possible to one quarter of the full sampler range, i.e., 32 for an 8-bit sampler, 64 for a 9-bit sampler, or 128 for a 10-bit sampler. Another approach that is operationally even simpler would be to set the attenuator as high as possible before losses become unacceptable and then simply leave the attenuator fixed thereafter. Since this value of attenuation is already the largest tolerable, there is no need to consider increasing it as the RFI grows. Slow changes in the overall system gain may, however, require attenuator adjustments from time to time. In either operational scenario, there is still value in monitoring the digitized signal levels frequently to know if, when, how strong, and at what frequencies the RFI is occurring.

4. Impact of RFI on the VLBI2010 DBE/DBBC

The back-end digital processors in modern VLBI data acquisition systems serve many functions ranging from phase cal extraction and radiometry to requantization and formatting of data for recording. But their most fundamental function is the separation of the data into frequency channels. There are two conceptually different ways of doing this.

One is a straightforward digital implementation of the classical analog Baseband Converter (BBC). This implementation includes digital equivalents of the BBC local oscillator, single sideband mixer, and baseband filters. As a result, its functionality is essentially equivalent to that of the BBC including flexible setting of the center frequencies and bandwidths of the channels. If flexibility is an issue or if only a comparatively few channels are required, this approach is preferred.

The second method for channelization is conceptually a digital filter bank [3]. It involves the use of a Polyphase Filter (PPF) followed by a Fast Fourier Transform (FFT). Over the years, extremely efficient algorithms have been developed to carry out these functions. However, this method is considerably less flexible as it forces all channels to be contiguous and to have the same bandwidth. If flexibility is not an issue and a comparatively large number of channels is required, this approach is preferred. It is the one selected for VLBI2010.

In order for the filter bank method to work effectively in the presence of RFI, it is necessary that there be adequate isolation between channels. In other words, if there is strong RFI in one channel, it is important that very little of the RFI leaks into its neighboring channels. This ensures that narrow band RFI will not degrade or destroy more than a single channel at a time. As it turns out, isolation as high as 60 dB between adjacent channels is routinely achieved with commonly used highly efficient PPF/FFT algorithms [3].

Another choice in the definition of the filter bank that is influenced by RFI is the channel bandwidth. If there is a lot of RFI in a given spectral region as happens for example in S-band, narrower bandwidth channels make it possible to acquire good data in the spaces between the RFI. Recall that any significant RFI in a given channel destroys the whole channel and not just the spectral region in which the RFI occurs. At the VLBI2010 Workshop on Future Radio Frequencies and Feeds (FRFF) in March 2009, Roberto Ambrosini presented a sample spectrum of RFI taken at the IVS Network Station Medicina [1]. Assuming a 1-GHz VLBI2010 band centered on 2.5 GHz, a simple analysis of this sample spectrum [2] found that the amount of usable spectrum increased by nearly a factor of two from just over 400 MHz to just under 800 MHz when the channel bandwidth was decreased from 32 to 2 MHz.

5. RFI in the 2-14 GHz Range

The entire radio spectrum from 2-14 GHz is allocated to one application or another. In the frequency range from 2.2-3.0 GHz, the U.S. regulations show over 70 separate allocations. Due to the distribution and operating modes of emitters, the RFI environment varies significantly from location to location and from time to time.

In many ways, urban areas, due to their greater population density, provide a more congested RFI environment. However, rural areas have their own challenges. In these areas, the laying of cables for communication and broadcast purposes is less cost effective and is often replaced by the use of airwaves. In addition, transportation routes through urban, rural, and remote areas, whether by land, sea, or air, all suffer from RFI related to the need for long-range mobile communications, radio-navigation, radiolocation, and weather surveillance. For the same reasons, airports, seaports, and military installations represent heavy concentrations of RFI emitters, both mobile and fixed.

It is recommended that site selection criterion for new VLBI2010 sites include a thorough RFI evaluation. It is further recommended that all VLBI sites make themselves and their spectrum needs known to local regulators so that appropriate considerations can be applied when applications for new emitters are processed.

There is one class of RFI emitters with nearly equal impact at all locations, those being space based emitters. Of particular concern are the emissions from geostationary Direct Broadcast Satellites (DBS) in the broad frequency ranges of 3.7–4.2 GHz (C-band) and 10.7–12.75 GHz (Ku-band). There are literally hundreds of DBSs (e.g., http://www.geo-orbit.org) in orbit, all at roughly 36,000 km altitude and directly above the equator. Signals are radiated into spot beams of varying sizes and the EIRP for the transmissions can range from below 40 dBW up to about 56 dBW. At these power levels, the DBS broadcasts cause no problems for VLBI2010 when received into the backlobes and far sidelobes of the VLBI antenna. However, when the VLBI antenna points within about 10 degrees of a satellite the received RFI begins to add noticeably to the system noise levels. Of course, the pointing distance from the satellite where this begins to be a problem depends on the exact power of the transmitter and the orientation of the spot beam. Given the large number of DBS satellites this could in fact represent the loss of a significant area of sky at many locations. Fortunately, the VLBI2010 frequency sequences have significant resilience against a single weaker channel. When this is coupled with judicious scheduling enhancements, it is likely that the 10.7 to 12.75 GHz region of the spectrum will be usable by VLBI2010.

Two final RFI sources should at least be mentioned. These are directly related to space geodesy and are potentially an issue if VLBI is to operate optimally at multi-technique sites that are the foundation of the International Association of Geodesy's (IAG's) Global Geodetic Observing System (GGOS). They are the DORIS beacon and the Satellite Laser Ranging (SLR) aircraft avoidance radar. The DORIS frequency is at about 2 GHz with a transmit power of about 9.5 W into an omnidirectional antenna, and the SLR radar frequency is at about 9.3 GHz with a transmit power of about 1 KW into a parabolic antenna. These are both fairly powerful transmitters. If it is desired that all three techniques (DORIS, VLBI, and SLR) operate simultaneously in close proximity (i.e., within a few hundred meters of each other), preliminary calculations indicate that it would be prudent to erect simple signal deflectors or absorbers to attenuate the DORIS and SLR radar signals on the line-of-site to the VLBI2010 antenna.

6. Acknowledgements

Most results in this paper are based on an IVS memo currently in preparation [2].

References

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